Probing Disk Accretion in Young Brown Dwarfs

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ABSTRACT

We present high-resolution optical spectra of 15 objects near or below the sub-stellar limit in the Upper Scorpius and ρ Ophiuchus star-forming regions. These spectra, obtained with the HIRES instrument on the Keck I telescope, are used to investigate disk accretion, rotation and activity in young very low mass objects. We report the detection of a broad, asymmetric Hα emission line in the ρ Oph source GY 5 which is also known to harbor mid-infrared excess, consistent with the presence of an accreting disk. The Hα profiles of the Upper Sco objects suggest little or no on-going accretion. Our results imply that if most brown dwarfs are born with disks, their accretion rates decrease rapidly, at timescales comparable to or smaller than those for T Tauri disks. The Upper Sco brown dwarfs appear to be rotating faster than their somewhat younger counterparts in Taurus, consistent with spin-up due to contraction following disk unlocking. The Hα activity is comparable to saturated activity levels in field M dwarfs with similar spectral type and rotation rates. Comparison of our data with published (albeit lower-resolution) spectra of a few of the same objects from other epochs suggests possible variability in accretion/activity indicators.

Subject headings: stars: low mass, brown dwarfs – stars: pre-main-sequence – circumstellar matter

1. Introduction

In their pre-main-sequence phase, low mass stars accrete high angular momentum material from a circumstellar disk. The star remains a comparatively slow rotator, however, apparently due to disk-locking, i.e., magnetic braking by large-scale stellar field lines that thread the disk. In the classical T Tauri phase, the fields may also mediate accretion by truncating the inner disk and channeling in infalling material (Königl 1991; Ostriker & Shu 1995). While many independent observations support this picture for stars with masses $>0.2M_{\odot}$, whether it applies to objects at or below the hydrogen-burning limit is only now being explored.

The formation mechanisms of brown dwarfs are still open to debate. Most recently, Padoan & Nordlund (2002) have argued that brown dwarfs form in the same way as more massive stars, via 'turbulent fragmentation'. Reipurth & Clarke (2001), on the other hand, suggested that brown dwarfs are stellar embryos ejected from newborn multiple systems before they accreted sufficient mass to eventually start hydrogen burning. In this model, dynamical interactions are expected to prune their disks. Studies of disk accretion, rotation and activity in young brown dwarfs could help distinguish between these scenarios. In particular, it is of considerable interest to investigate whether some or all young sub-stellar objects undergo a T Tauri-like phase and if so how long that phase lasts.

Accretion signatures have been seen already in high-resolution spectra of a few very low mass sources. Muzerolle et al. (2000) detected an asymmetric Hα line profile in the M6 object V410 Anon 13 in Taurus and used magnetospheric accretion models to show that it is accreting from a disk but at a much lower rate than that found in higher mass stars. White & Basri (2002) found two more Taurus M5.5-M6.5 objects with Hα profiles similar to other classical T Tauri stars.

Here we present high-resolution optical spectroscopy of a much larger sample of objects near or below the sub-stellar limit in the nearby ($\sim$ 150 pc) Upper Scorpius and ρ Ophiuchus star-forming regions. Our targets are sources with M5 or later spectral types from the surveys of Ardila, Martín, & Basri (2000) for Upper Sco and Wilking, Greene & Meyer (1999) for ρ Oph. Our goals are to search for broad, asymmetric Hα lines indicative of disk accretion, to measure rotational properties as denoted by $v\ sin\ i$, and to investigate chromospheric activity, in these young very low mass objects in comparison to their older counterparts in the field and to (higher-mass) T Tauri stars.

In a subsequent paper (Mohanty et al., in prep), we will use these optical spectra, together with observed photometry and theoretical isochrones, to derive effective temperatures, gravities, masses and ages for our sample objects. For the purposes of this paper, we assume an age of $\sim$ 1 Myr for ρ Oph and $\sim$ 5 Myr for Upper Sco (Preibisch & Zinnecker 1999). If we also assume that the effective temperatures of our young M5-M8 objects are comparable to those of field M dwarfs of the same spectral type ($\sim$ 3000-2500 K, similar to what is derived by Wilking, Greene & Meyer 1999 for their ρ Oph sample), then theoretical models (Chabrier et al. 2000) imply masses of $\sim 0.1 - 0.02\ M_{\odot}$. Thus, our sample spans a mass range from the stellar/sub-stellar boundary well into the brown dwarf domain.

2. Observations and Analysis

We obtained optical spectra of the target sample using the High Resolution Echelle Spectrometer (HIRES; Vogt et al. 1994) on the Keck I telescope on 2002 May 19 and 20 UT. With the 1.15" slit, the two-pixel-binned spectral resolution is R $\approx$ 33,000. The instrument yielded 15 spectral orders in the 6390 – 8700 Å wavelength range, with gaps between the orders, providing a variety of features related to youth and accretion activity. For comparison to our targets and to derive *v sin i*, we used M dwarf and M giant spectroscopic standards observed with the same HIRES set up. The data were reduced in a standard manner using IDL routines, as described in Basri et al. (2000).

We derived rotational velocities (*v sin i*) of the targets by cross-correlating with a 'spun-up' template of a slowly rotating standard. Multiple spectral orders ($\sim$ 6), selected on the basis of an absence of strong telluric features, strong gravity-sensitive features, and stellar emission lines, were used in the cross-correlation analysis. Following White & Basri (2002), we used a combination of giant and dwarf spectra for the template.

3. Results and Discussion

Table 1 lists the equivalent widths of Li I and Hα lines, full widths at 10% of the peak flux level of Hα, and *v sin i* values of our sample, along with the relevant error estimates. Of our 14 targets in Upper Sco, 11 show Lithium 6708 Å absorption and have similar radial velocities (standard deviation $\sim$ 2 kms^{-1}). The remaining three (USco 85, USco 99 and USco 121) do not show Lithium, and are likely non-members; we do not discuss them further. Except for GY 5, our ρ Oph sources do not have sufficient signal-to-noise in the blue to measure Li equivalent widths, primarily because they suffer from significant extinction. However, their membership in the ρ Oph molecular cloud has been established by Wilking, Greene & Meyer (1999) using near-infrared photometry and spectroscopy.

Figure 1 shows Hα line profiles of our sample. The ρ Oph source GY 5 exhibits a broad, asymmetric Hα profile while none of the Upper Sco targets do. There is evidence of a measurable change in the Hα emission of USco 128 between two observations separated by about an hour.

3.1. Disk Accretion

Accreting ("classical") T Tauri stars exhibit strong, broad Hα line profiles indicative of high velocities in a nearly free-falling flow (e.g., Hartmann, Hewett, & Calvet 1994). Weak-line T Tauri stars, on the other hand, harbor weak, narrow Hα lines, presumably originating in their active chromospheres. The equivalent width of the Hα line is often used to distinguish between these two types of objects. However, the threshold value of Hα equivalent width depends on the spectral type (Martín 1998). White & Basri (2002) suggested full-width at 10% of the peak emission as a more accurate empirical indicator of accretion than either the Hα equivalent width or optical veiling: 10% widths > 270 kms^{-1} indicate accretion *independent of the stellar spectral type*.

The ρ Oph source GY 5 has a 10% Hα width of 352 kms^{-1} (and an equivalent width of 65 Å): it appears to be undergoing accretion. Interestingly, it is one of the sources with a mid-infrared excess detected by the Infrared Space Observatory (ISO), consistent with the presence of a circumstellar disk (Comeron et al. 1998; Bontemps et al. 2001; Natta et al. 2002). Thus, GY 5 may be the first spectroscopically confirmed sub-stellar object with an accreting disk detected via infrared excess as well as Hα characteristics. Surprisingly, Wilking, Greene, & Meyer (1999) did not see Hα emission (< 5 Å) in their low-resolution optical spectrum of GY 5 (albeit obtained "under nonideal conditions"). It may be that the accretion onto GY 5 is highly variable (or highly asymmetric so that geometric effects are important).

According to ISO mid-infrared flux measurements, GY 141 and GY 310 also harbor excess emission but GY 37 does not (Comeron et al. 1998; Bontemps et al. 2001). Hα line profiles in our optical spectra do not show clear evidence of on-going accretion in any of these three objects. Given the problems of extinction, it would be interesting to obtain near-infrared spectra of all ρ Oph sources to investigate other accretion signatures such as Pa β and Br γ. Given the large ISO beam, it would also be prudent to confirm via high angular resolution observations (e.g., ground-based L- and N-band imaging) that the mid-infrared sources indeed coincide with the brown dwarfs.

By the White & Basri (2002) criterion, none of the Upper Sco objects in our sample shows evidence of on-going accretion. The case of USco 128, however, is intriguing. In low-resolution spectra, Ardila et al. (2000) reported a 'constant' Hα equivalent width of 130 Å in two observations separated by a month. Our two HIRES spectra, separated by just one hour, yield equivalent widths of 16 and 25 Å; i.e., there was a measurable change in the line over a short time interval (see Fig. 1). While it is true that low-resolution spectra of late-type objects systematically overestimate Hα as a result of blending with the 6569 Å TiO band-head, a factor of $\sim$5 difference between the Ardila et al. (2000) values and ours is difficult to account for in this way. However, variation in the Hα width by more than a factor of 5 is not uncommon in flares. It may be that chromospheric activity in USco 128 is highly variable. In that case, the large width reported by Ardila et al. (2000) may correspond to a period of sustained high activity and flaring.

The mean age of stars in the Upper Sco region is $\sim$5 Myr whereas ρ Oph sources are even younger at $\sim$1 Myr (e.g., Preibisch & Zinnecker 1999). Our results suggest that if most brown dwarfs are born with disks, their accretion rates decrease rapidly, within the first few million years. Such a conclusion is also consistent with measurements of disk frequency as a function of age using infrared excess. While a large fraction –$\sim$60%– of brown dwarf candidates in the $\sim$1-Myr-old Trapezium cluster show near-infrared excess (Muench et al. 2001), the fraction appears to be much lower in the somewhat older σ Orionis ($\sim$3-8 Myr) and TW Hydrae ($\sim$10 Myr) associations (Jayawardhana, Ardila & Stelzer 2002). Thus, it appears that at least the inner disks of brown dwarfs deplete rather quickly, at timescales comparable to or smaller than those for T Tauri stars (Jayawardhana et al. 1999). Disk dissipation timescales in Upper Sco might be even shorter than in some other star-forming regions due to strong winds and ionizing radiation from numerous luminous stars in its midst (Preibisch & Zinnecker 1999 and references therein). Studies of large samples of brown dwarfs in several young clusters, spanning a range of ages and environments, will provide a more definitive answer.

3.2. Stellar Rotation and Activity

Measures of stellar rotation and chromospheric activity in young brown dwarfs, in comparison with their older counterparts in the field and higher-mass coeval T Tauri stars, can shed light on a variety of questions, from the nature of sub-stellar magnetic fields to the efficiency of disk locking.

A large fraction of the lowest-mass stars in Orion appear to be fast rotators whereas Taurus objects of similar spectral type rotate much more slowly (Clarke & Bouvier 2000; Herbst et al. 2001; White & Basri 2002). According to a scenario advocated by Hartmann (2002), late-type Orion objects have not yet had time to slow down via disk braking whereas (somewhat older) Taurus objects have. In the standard picture, following disk unlocking, the low-mass stars (and presumably brown dwarfs) would spin up again. Eventually, braking by magnetized winds is expected to slow the stars down again, though it appears that such braking may not be efficient in the lowest mass stars and brown dwarfs (Mohanty & Basri 2002a; Mohanty & Basri 2002b). In the first few Myr, in any case, contraction timescales are expected to be much shorter than braking timescales, so spin-up is expected to dominate (once the disk locking ends) over this period (Bouvier, Forestini & Allain 1997).

Among the ρ Oph targets, we find $v\ sin\ i \approx 14$ kms^{-1} in GY 5, which very likely harbors a disk. It is interesting to note that GY 141 and GY 310, which also show mid-infrared excess, are relatively slow rotators (~ 6 and 10 kms^{-1}, respectively) while GY 37, which does not show a mid-infrared excess, is a rapid rotator (~ 22 kms^{-1}). This may be a hint of disk-locking in action, though further observations and a larger sample are required for verification.

Among the 11 Upper Sco members in our sample (all apparently non-accretors), six show rotational velocities $v\ sin\ i > 15$ kms^{-1}. The average $v\ sin\ i$ of the Upper Sco sample is ~ 25 kms^{-1}. In seven similar mass non-accretors in Taurus, on the other hand, White & Basri (2002) find an average $v\ sin\ i$ of ~ 10 kms^{-1}, with only one object rotating above 15 kms^{-1}. Thus, the Upper Sco brown dwarfs appear to be rotating noticeably faster than their Taurus counterparts. Since Upper Sco is believed to be somewhat older than Taurus, we may be seeing the signature of spin-up due to gravitational contraction following disk unlocking.

In our Upper Sco sample, the equivalent widths of Hα arising from chromospheric activity are in the range $\sim$ 6-18 Å (except one larger width in USco 128). Without accurate effective temperature determinations, we cannot yet calculate the Hα fluxes these widths correspond to. However, the Hα widths are comparable to saturated widths in field M dwarfs of similar spectral type (Mohanty & Basri 2002a; Mohanty & Basri 2002b). Thus, if the effective temperatures of the Upper Sco objects are similar to those of field dwarfs of the same spectral type, then their Hα fluxes would correspond to saturated levels in the field. This issue will be investigated further in a subsequent paper (Mohanty et al., in prep).

4. Summary

We have explored disk accretion, stellar rotation and chromospheric activity in a substantial sample of young brown dwarfs in the Upper Sco and ρ Oph star-forming regions using high-resolution optical spectra from the HIRES instrument on the Keck I telescope.

We have detected evidence of accretion in the ρ Oph source GY 5 in the form of a broad, asymmetric Hα emission line. Interestingly, GY 5 also has a mid-infrared excess detected by ISO consistent with the presence of a disk. The Hα profiles of our Upper Sco targets suggest little or no on-going accretion. It appears that if most brown dwarfs are born with disks, their accretion rates decrease rapidly, on timescales comparable to or shorter than those for T Tauri disks. On average, the Upper Sco brown dwarfs are rotating faster than their somewhat younger counterparts in Taurus, which may be a hint of spin-up due to contraction once the disk locking has ended. Their chromospheric activity levels, as indicated by Hα, are comparable to the saturated activity levels seen in field objects of similar spectral type. Our results, in comparison with similar studies of other young clusters spanning a range of ages and environments, will help unveil the origin and early evolution of sub-stellar objects.

We thank the Keck Observatory staff for their outstanding support, and David Ardila, Beate Stelzer and Russel White for useful conversations. This work was supported in part by NSF grants AST-0205130 to RJ and AST-0098468 to GB.

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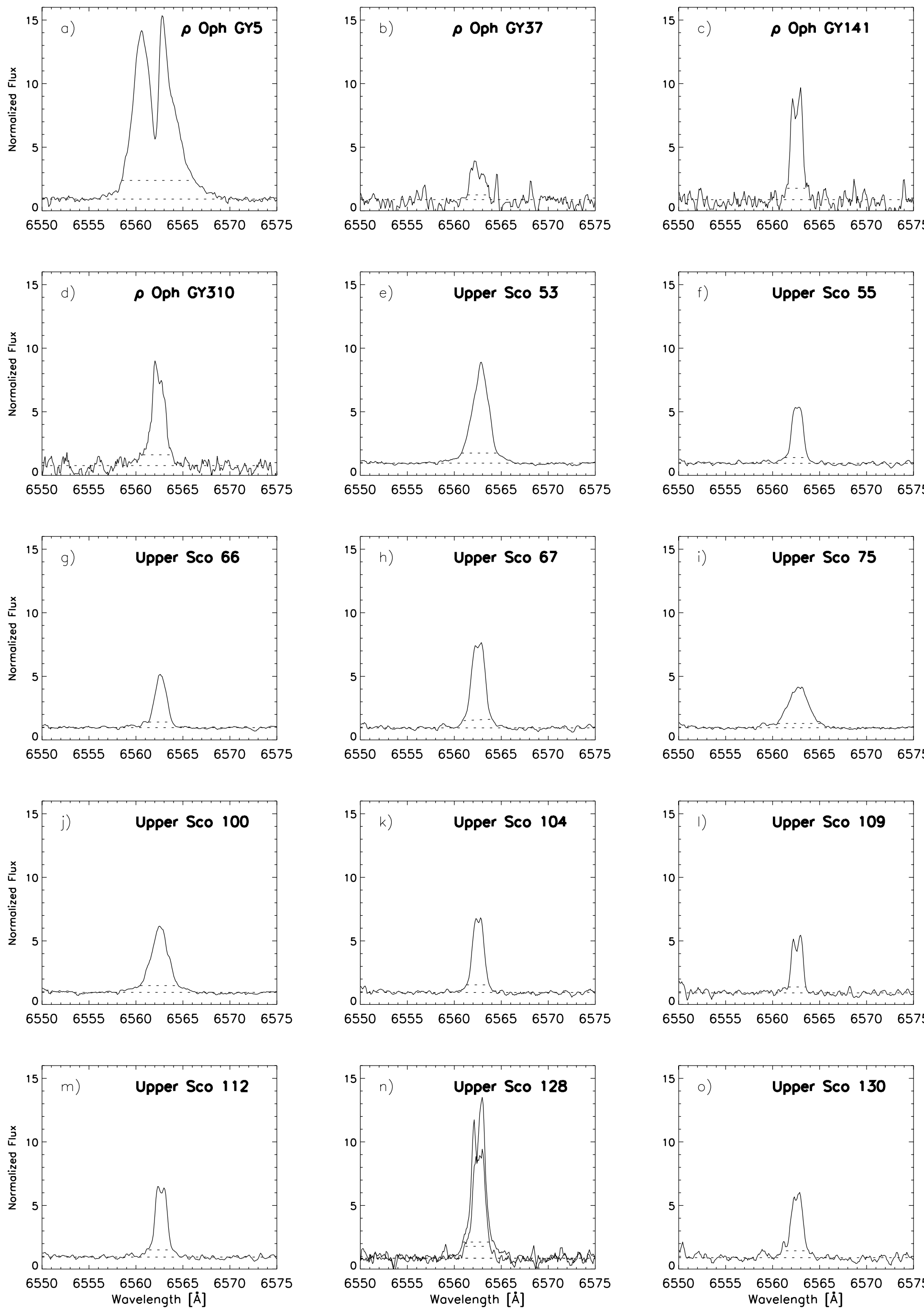

Fig. 1.— Hα line profiles of the target sample. Spectra shown have been smoothed by a 3-pixel boxcar; continuum and full width at 10% of the peak levels are marked by dotted lines.

Table 1.

Object	Sp Type[a]	v *sin* i (kms^{-1})	Li EqW[b] (Å)	Hα EqW[b] (Å)	Hα 10% FW (kms^{-1})
ρ Oph GY5	M7	16±2	0.3:	64.9±1.5	352
ρ Oph GY37	M6	22.5±5	-	5.1:	102:
ρ Oph GY141	M8.5	6±3	-	13.4±0.2	87
ρ Oph GY310	M8.5	10±3	-	17.2±0.2	144
USco 53	M5	45±2.5	0.7	17.8±0.4	175
USco 55	M5.5	12±3	0.6	7.3±0.3	114
USco 66	M6	27.5±2.5	0.7	6.5±0.2	115
USco 67	M5.5	18±2	0.7	12.9±0.2	139
USco 75	M6	62.5±5	0.8	8.9±0.2	212
USco 100	M7	50±3	0.7	13.1±0.4	184
USco 104	M5	16±2	0.6	9.4±0.3	109
USco 109	M6	6±2	0.7	6.3±0.2	84
USco 112	M5.5	5.5±2	0.6	9.5±0.3	111
USco 128	M7	<5[c]	0.6:[c]	15.9±0.7	121
				24.8±1.7	147
USco 130	M7-M8	14±2	0.6	8.4±0.3	111

[a]Spectral types for ρ Oph sources are from Wilking, Greene & Meyer (1999); spectral types for Upper Sco targets are from Ardila et al. (2000)

[b]*Pseudo*-equivalent width; the plethora of molecular lines make it impossible to determine the true continuum

[c]Calculated from coadding the two spectra